Defense Technical Information Center Compilation Part Notice

ADP010327

TITLE: Advances in UAV Data Links: Analysis of Requirement Evolution and Implications on Future Equipment

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: Advances in Vehicle Systems Concepts and Integration. [les Avancees en concepts systemes pour vehicules et en integration]

To order the complete compilation report, use: ADA381871

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, ect. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:

ADP010300 thru ADP010339

Advances in UAV Data Links: Analysis of Requirement evolution and implications on future equipment

S.Baiotti, G.L.Scazzola, G.Battaini, E.Crovari
Marconi Communications S.p.A.
Defence Communications Division - Guided Systems
Via A.Negrone 1A - 16153 GENOA
ITALY

1. ABSTRACT

This paper resumes the fundamental operational requirements that a UAV must accomplish to be effectively performant in a military and civil environment. Moving from these considerations, a list of technical requirements for Data Link systems to be employed is derived and a suitable Data Link architecture, based on the evolution of current Marconi's J-Band Data Link for CATRIN-SORAO programme is presented.

2. INTRODUCTION

UAVs (Unmanned Air Vehicles) are getting higher and higher importance in the last years' battlefield scenarios and, in general, in a variety of military operations such as ground surveillance, peace keeping and battle damage assessment. The experiences gained by U.S. Army Forces during the Gulf War and by NATO Forces in recent Bosnia operations have demonstrated that UAVs can play a crucial role everytime a complete situation awareness of a hostile or sub-hostile territory is needed. Moreover, use of UAVs for civil applications is still at an early stage, but is growing rapidly in some countries such as Japan. However, wide employment of these aircrafts calls for a series of improvements in performance and reliability and requires a growing level of integration with both military and civil air traffic control systems. This paper will address all these issues and their consequences on new Data Links architectures.

3. SCOPE OF THE PAPER

Scope of this paper is to analyse typical UAVs requirements to be fulfilled, to present some considerations on technical characteristics of all communication systems involved and to derive, on the basis of Marconi Communications experience, a possible architecture for newly designed Data Links.
This work will be outlined as follows:

- Section 4 presents some emerging UAV operational requirements introduced by new scenarios and possible applications.
- Section 5 relates on technical UAV Data Link requirements and presents some related design considerations. The matter is subdivided in two parts: the first one (Sec. 5.1) briefly lists those requirements that can be considered as "consolidated" and virtually constitute the basis of every UAV system; the second one (Sec.5.2) relates to issues to be considered to accomplish new operational requirements.
- Section 6 presents a possible architecture based on preceding considerations.

4. UAV OPERATIONAL REQUIREMENTS

With respect to the past, some present requirements have to be extended or modified while some new ones have arisen. In the following this requirement evolution will be examined in greater detail.

4.1 More extended and complex military scenarios

Usage of Tactical UAVs is more and more frequent in such operations as peace keeping or ground surveillance over crisis zones; in many cases, military Forces taking part of missions act as a "third party" not directly involved in local warfare situations. This often implies the ability for a Tactical UAV to operate over wider areas than in the past, while maintaining its ground-based control centre outside the boundaries of the country to survey. Moreover, rapid deployment of ground equipments near the operation territory could be extremely risky in presence of guerrilla-organised troops or could be difficult due to lack of logistic facilities (roads, airports, etc.). All these issues have increased the operational range requirements: at the present a limit of 200 Km can be considered as necessary for Tactical UAVs; for Medium Altitude Endurance UAVs (MAE UAVs) this limit must be raised up to 1000 Km.

4.2 Multi-sensors capability

For a UAV to be capable to operate effectively in most meteorological and operational conditions, use of different types of sensors is requested: for instance, IR sensors can be useful for night surveillance at short-medium distance from the targets, but a SAR sensor would allow better targets resolution at relatively higher ranges. For all these reasons, UAVs should be capable to host different sensors (possibly more than one at the same time) and a Data Link system able to collect their data and transmit them to the Ground Control Station.

4.3 Data dissemination and communication issues

Rapid deployment of a communication network for data exchange between Tactical Command & Control centre and some Ground Units spreaded over the territory can be difficult, especially in presence of natural obstacles (mountains and valleys) that can limit the functionality of terrestrial communication devices such as VHF radio equipments or line-of-sight (LOS) data links. In these cases, the UAV Data Link system can be equipped with an additional broadcasting function in order to directly disseminate sensors and tactical data over a wide area or connect locally a small number of Ground Units: this can represent a valid alternative to satellite communication equipments, that often suffer from lack of available channels and usually offer less channel bandwidth. Moreover, satellite

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

links are generally characterised by lower ECM resistance, higher interceptability and higher latency with respect to wide band Data Links for UAV.

4.4 Operations over civil areas

Another practical effect of considerations presented in Sec. 4.1 is the need to fly over both military and civil areas of one or more countries (possibly not involved in the operations), thus potentially interfering in commercial airways and introducing a wide series of problems concerning flight safety. This calls for a growing level of integration with present Air Traffic Control (ATC) and future Air Traffic Management (ATM) to ensure that the UAV can be properly monitored (even if not directly controlled) during non operational phases of flight and during possible manoeuvres (including takeoff and landing) in proximity of airports open to civil traffic. A further improvement of overall reliability of UAVs and, in particular, their communication systems is also required.

4.5 Non-military applications

Ground surveillance through a UAV can also have importance in a wide series of non-military applications: for example, during search and rescue operations over sea and land (in case of natural calamity such as earthquakes, floodings, etc.) whenever meteorological conditions or other factors can determine too risky conditions for a manned aircraft. Other possible applications can be coastal surveillance (for illegal immigration and smuggling control purposes), police operations and agricultural aid (for fertilizer distribution, etc.). With respect to military applications, a civil UAV presents less security constraints (e.g. ECCM capability, etc.) but requires all the features indicated in Section 4.4 to fly over civil areas.

4.6 UAV for non-lethal weapons deployment

Non-lethal weapons (including foams, nets, irritants, obscurants, acoustic devices, optical munitions, etc.) are those weapons designed to degrade the capabilities of material or personnel and yet avoid unintentional human casualties. Use of non-lethal weapons for police, peace-keeping and military application is becoming wider and wider and UAV appear to be an ideal platform for non-lethal weapons deployment in many scenarios. From a data link point of view, this application involves again the issues described in Sec. 4.2 and Sec. 4.4 (i.e. multi-sensor capability and operations over civil areas), but further additional requirements arise, associated to the authorisation to release the non-lethal weapons: for safety and legal reasons high availability / reliability and very low bit error rate are required for the data link to transmit these commands.

4.7 Uninhabited Combat Air Vehicles

At present Uninhabited Combat Air Vehicles (UCAVs) are one of the applications more debated by the UAV Community: if feasible, a UAV, capable to substitute manned fighters in the missions with the highest risk for the crew (such as low quote ground attack and/or Suppression of Enemy Air Defenses (SEAD)), would find a very high interest by the Military Forces. UCAVs however are expected to enter in service at long term (after 2010) as their design presents technical issues considered very critical, concerning mainly two areas: the demanding artificial intelligence required, related to UCAV autonomous situation awareness and decision planning, and the complex communication system, that, according to research / pre-feasibility activities being performed in the world (including the NIAG SG 53 Study "UAV Interoperability"), appears to be well above the technical characteristics of present state-of-the-art UAV data link systems. From a communication perspective, main issues concerning UCAVs are:

- **UCAV control/monitoring in combined missions**: UCAVs are envisaged to perform their missions in complex scenarios where several types of aircraft and also Ground and Naval Forces may be present; UCAVs and manned aircraft may be involved in combined attacks. Two main functions are required to the UCAV data link system: the first is to allow UCAV control / monitoring in all the mission phases by different platform (airborne, shipborne or land-based) one at a time; the second is to ensure the UCAV integration in the air situation awareness network, exploiting UCAV data according to criteria used for other aircraft. The communication systems architecture needs to fulfil these two functions, which impose different and sometimes opposite requirements.
- **Link integrity / ECM robustness**: in a UCAV all main functions (including weapons control) depend on data link system control/monitoring. Moreover, ECM environment is envisaged to be very severe, as UCAVs are planned to be used also in SEAD missions. Link integrity and ECM robustness requirements appear therefore very demanding.
- **Link availability / reliability**: UCAV operations need an overall data link availability (including atmospheric fading, multi-path losses, antennas misalignment, etc.) higher than 99%, well above the 90-95 % typically required to UAV payload wideband data link. High overall reliability is also required for the data link system, recommending either equipment redundancy or re-configuration capability.
- **Beyond line-of-sight UCAV control**: typical UCAV missions (ground attack, SEAD, etc.) involve low quote operation at range of hundreds of Km; the data link system is required to ensure high band and low latency connections to allow continous and reliable UCAV control also in these conditions.

4.8 Interoperability

Interoperability becomes highly desirable when UAV has to be used in a multi-national environment or, in general, when multiple UAV systems must coexist in the same scenario.

A NIAG group (NIAG SG53) has been established in 1997 to define design recommendations and is now at the end of its effort. Five nested levels of interoperability have been defined, starting from standardisation of interfaces/protocol of Ground Stations to guarantee flexible interconnectivity to C^3I networks (Level 1) and arriving to complete UAV and payload control capability by different Ground Stations, including takeoff and landing phases (Level 5).

Interoperability can lead to a variety of advantages (in terms of interfaces, protocol, data format standardisation, etc.) and, consequently, to cost reduction and usage flexibility (due to modules interchangeability). On the other hand, some constraints and drawbacks arise in the short term: for instance, backward compatibility towards existing systems is often required and this implies the design of legacy units to act as interface. Moreover,

high level of standardisation can potentially limit the design flexibility or even lead to lower efficiency: for example, usage of standard protocol such as TCP/IP to convey data over Data Link channel can reduce throughput due to the data overhead required; for limited channel bandwidth and high sensor data rate a dedicated protocol can be more suitable. All these matters must be taken into account during Data Link system design.

5. DATA LINK TECHNICAL REQUIREMENTS

5.1 Consolidated requirements

The following requirements are necessary to guarantee a suitable operativity and appear to be almost completely acknowledged by all state-of-the-art systems:

- Operational range: up to 100 NM for Tactical UAVs and up to 500 NM for MAE UAVs
- Availability over 90%
- Low bit error rate on Data Link (between 10^{-3} and 10^{-6} according to data type)
- Low interceptability
- High resistance to ECM
- Low latency for UAV/Payload Command and Control Data
- Limited size, weight and power consumption (SWP)

For instance, Marconi Communications' Data Link for CATRIN accomplishes all requirements for Tactical UAVs: it operates in J band (NATO harmonised band for Mobile Systems) and has a range of up to 100 Km @ 2 Mbit/s (now extendable up to 180 Km through an external Booster Module). It operates on a Time Division Multiplex basis to provide bidirectional communications while accomplishing SWP constraints. It offers high ECCM protection thanks to Frequency Hopping techniques. Further details are listed in [1], while current development activities are described in Sec.6.

5.2 Innovative requirements and design considerations

5.2.1 *EXTENDED RANGE*

New requirements in operational range (i.e. over 200 Km for Tactical UAV) can be fulfilled in different ways: increasing receiver sensitivity, adopting ground and airborne antennas with higher gain and increasing transmitted power.
The first approach appears difficult to be followed: provided that modulation scheme remains fixed, larger bit rates requested by new sensors determine lower sensitivity at the receiver (S/N ratio decreases by 6 dB for a 4 times increment in bandwidth: this means that range reduces by a factor 0.5 for fixed BER, trasmission frequency and modulation scheme). Changing type of modulation (e.g. from MSK to 16-PSK) can reduce the bit rate onto the channel by a factor of 2, but this gain become vanishing if we consider that a 16-PSK receiver is about 4 dB less efficient than MSK type. A good compromise can be reached by selecting suitable data rates depending on sensor type (see Sec. 5.2.3).
The second solution is potentially feasible but implies more directive antennas: these ones require to be installed onto a stabilised platform or, at least, need to be steerable in azimuth and elevation plane to compensate for UAV attitude angles during flight.
Finally, longer ranges can be reached increasing transmission power: nowadays level as high as 20-30 W can be obtained through solid-state devices, offering high reliability and relatively good efficience. Higher power levels (around 100 W) can be reached using vacuum tube amplifiers: they are now available in small housings, suitable to be used even for airborne applications. The actual feasibility depends on SWP constraints, especially those related to the Airborne Data Terminal (ADT).

5.2.2 *BIT ERROR RATE*

Bit error rate (BER) is a primary issue for every Data Link system and in particular for UAV Data Link. Since this is an unmanned vehicle, two levels of channel integrity can be pointed out: from the communication point of view, Data Link must ensure enough low BER to allow effective exploitation of sensors data; on the other hand, it must guarantee high Command&Control reliability during critical phases such as flying over civil areas or during takeoff and landing. For the first issue, due to higher data autocorrelation, especially if related to images, typical acceptable BER is around 10^{-3}-10^{-4}, while in the latter case acceptable values decrease to 10^{-6} - 10^{-9}. All these considerations must be furtherly stressed when related to a UCAV. Since obtaining extremely low physical BER levels on the Data Link channel implies heavy drawbacks on link budget, a better approach consist in reaching a suitable physical channel BER to guarantee sensors data exploitation in most cases, paying attention on BER effects on compressed data (see Sec. 5.2.4) and applying suitable error corrections techniques to selected data (see Sec. 6.1.5) in order to limit their overall error rate to the lowest values indicated above.

5.2.3 *ENHANCED DATA RATE*

The common trend in UAV Data Link performance requirements is oriented towards growing transmission rates: use of SAR (not preprocessed) or high definition EO sensors implies data rates of tenths of Mbit/s; more sophisticated sensors such as LOROP can reach hundreds of Mbit/s. As indicated in Sec. 5.2.1, high bit rate over trasmission channel means large signal bandwidth, thus lower receiver sensitivity and need for higher transmission power. However, this is not the only drawback: for example, if coherent demodulation is adopted to improve modem performance, carrier synchronisation can become a major issue when high trasmission speeds are chosen, leading to modem/synthesiser cost enhancement. Nonetheless, adoption of more complex, constant signal envelope modulation schemes, such as multi-h CPM, implies great trasmitter/receiver complication.
From the above considerations, the following design drivers can be derived: physical channel data rate should be limited at a suitable value, considering the trade-offs between transmitted power, SWP constraints and receiver/modem performances; the gap between physical bit rate and sensor bit rate should then be filled by an efficient data compression technique. A good compromise could be a physical data rate between 2 and 10 Mbit/s associated to a data compression ratio of about 15:1÷20:1 (see Sec. 5.2.4). For particular applications, data rates as high as 45-50 Mbit/s can be considered, provided that the transmitted power is increased to maintain the operational range.

5.2.4 *DATA COMPRESSION*

Data compression becomes mandatory when high definition sensors such as SAR and high resolution EO/IR cameras are mounted on UAVs. In this case, the high bit rate requested (and the related larger bandwidth) could drastically reduce the operational range of Data Link. Compression can help to maintain the physical data rate over the channel at lower levels with respect to uncompressed data transmission.
Efficient compression for EO and IR sensors has already been implemented by Marconi Communications in its Data Link for CATRIN-SORAO programme [1]. Further development activities are in progress to extend compression capability to SAR sensors: a specific study has been performed to recognize the compression technique that best fits the new operational requirements; its results are outlined in the following sections.

5.2.4.1 *Lossless techniques*

Lossless techniques are based on elimination of redundancy associated to the signal: the higher is the redundancy, the more effective is the compression. For instance, let us consider a signal derived from sampling of a video image produced by an EO sensor: adjacent pixels are usually mutually correlated and this feature can be exploited to transmit only essential information (e.g. difference between two pixels). Lossless techniques rely on reversible transforms that permits a complete signal reconstruction at the receiver end; they usually allow low compression rates (typically less than 4:1) and their performance heavily depends on signal type. For all these reasons they do not appear suitable to be implemented in Data Link systems for UAV.

5.2.4.2 *Lossy techniques*

Lossy techniques can reach higher compression rates by associating the concepts listed in the previous paragraph to space-frequency bidimensional transforms and quantisation: only the most significant part of signal informative content is trasmitted over the channel. This inevitably leads to a distorsion of the original signal that cannot be recovered at the receiver end. Apart from subjective figures of merit (such as "compression is effective if the reconstructed image is much similar to the original one"), some objective index of quality can be defined: the most used are the Minimum-Square-Error (MSE) and the Peak Signal-to-Noise Ratio (PSNR); both are referred to differences between each pixel of original and reconstructed image and are defined as following:

$$MSE = \frac{1}{MN}\sum_{i=1}^{N}\sum_{j=1}^{M}[f(i,j) - \hat{f}(i,j)]^2$$

$$PSNR = 20 * Log(\frac{255}{\sqrt{MSE}})$$

where $f(i,j)$ and $\hat{f}(i,j)$ are, respectively, the transform coefficients before and after quantisation, while M and N are the number of pixels along image axes. The term 255 in PSNR formula derives from the fact that images with 8 bit/pixel have been considered.

Provided that a technique featuring optimum performance for all types of data cannot be defined, Marconi's study has defined those ones that best adapt to typical imaging sensors hosted on UAV: EO/IR sensors and SAR. The results are depicted following:

- JPEG: it is one of the most used techniques and it is based upon Direct Cosine Transform applied to square pixel blocks and subsequent quantisation of transformed coefficients.
  Advantages: this technique is highly standardised, allows fast compression/decompression and high compression rates (up to 25:1 with low optical quality degradation and PSNR). Also, it features minimum latency for real-time applications (compression can be applied as soon as all pixels belonging to a block are available, without waiting for the whole frame) and shows low sensitivity to BER (bits received uncorrectly affect only small image portions). Finally, a wide series of commercial dedicated hardware is available.
  Disadvantages: high compressed images presents the "blocking" effect, due to fact that single image portions are processed separately. This effect is particularly evident in low contrast images: therefore JPEG often give better results with EO images than with IR or SAR images.

- WAVELET: a suite of similar techniques is encompassed under this name, but not all are completely standardised; in general, they are based upon a recursive bidimensional Fourier-like transform of each frame; at each step, higher frequency are eliminated and lower frequencies are undersampled, thus performing compression.
  Advantages:wavelet techniques shows high efficiency, allows high compression rates (up to 30:1 with low optical degradation) and less distorsion on low contrast images ("blocking" effect is not present).
  Disadvantages: unfortunately, these techniques usually require high compression/decompression time due to algorithm complexity and introduce higher latency, because compression has to be performed over a whole frame at a time. Moreover, resolution of small objects can be reduced, since contours appear as "smoothed" at high compression rates, and a high sensitivity to BER must be taken into account (errors on received data flow can have destroying effects on the whole reconstructed image). Finally, less commercial dedicated hardware is available (many high efficiency algorithm have been identified, but their practical implementation is difficult).

In Figure 1 to Figure 6 some examples of JPEG and Wavelet compression effects on IR and SAR images are presented: they are extracted from our feasibility study realised for Alenia Difesa - Italy in July 1998. "Blocking" effect does not assume particular importance in Figure 2 (JPEG compressed), since the image has a high contrast; therefore, no significant differences can be pointed out with respect to Figure3 (compressed with Wavelet transform). On the other hand, blocks are clearly visible in Figure 5, where a high compression ratio has been used on a low contrast SAR image, while Figure 6 appears better at a direct observation. This does not necessarily mean that an Automatic Target Recognition (ATR) algorithm would work better on Wavelet compressed images, due to the "smoothing" effect clearly visible in both Figure3 and Figure 6. Furthermore, a comparison between compression/ decompression times (for non-real time algorithms running on Silicon Graphics' Indy™ workstations equipped with R4400/200 MHz processor and 32 Mbyte RAM) and between distorsion parameters (PSNR and MSE) is presented in Table 1. It is apparent that JPEG algorithm

allows much faster coding and decoding than Wavelet; on the other hand, MSE and PSNR are comparable: it has been verified that MSE is typically slightly better for JPEG, while Wavelet works better in terms of PSNR.

In the end, both techniques are theoretically able to accomplish all data rate requirements indicated in Sec.5.2.3, provided that compression ratio is suitably limited. A maximum compression ratio of 15:1÷20:1 can support the most part of sensors likely to be hosted on a UAV while maintaining a satisfactory image quality level (even if usage of ATR algorithms is required). At the moment, JPEG still seems to allow easier implementation than Wavelet and has better overall performances for real-time applications; nevertheless Wavelet is open to improvement in the near future.

5.2.5 *MULTI-SENSOR CAPABILITY AND EXTERNAL INTERFACES*

Transmission of EO, IR and MTI sensor data has already been implemented in Marconi's Data Link for CATRIN-SORAO programme, even if in different HW configurations. Current aim is to accomplish, as far as possible, the requirements listed in Sec. 4.2 and 4.8 through a ADT and GDT configuration, capable to operate with one or more standardised sensors of different type at the same time and ensuring maximum payload interoperability and interchangeability.

A possible solution is to introduce on both ADT and GDT terminals a standard interface such as Fast Ethernet supporting a standard network protocol such as TCP/IP: this configuration provides a high speed connection (up to 100 Mbit/s) virtually independent from data format and relatively simple to to be implemented via a standard copper medium (single/double twisted pair). Moreover, Fast Ethernet is a widely diffused interface and many manufacturers of COTS HW can be found on the market: this could be helpful if cost reduction is required. Both EO, IR, MTI and SAR sensors can be supported, possibly in a single or multiple configuration, provided they are also equipped with a compatible interface and they are connected onto a dedicated bus. The only limitation is due to maximum bit rate: for instance, in case of multi-sensors configuration, overall throughput must be subdivided among users; also, a bit rate reduction factor related to bus collisions must be taken into account. TCP/IP protocol guarantees data multiplexing at the ADT end and data demultiplexing at the GDT end.

With reference to ADT architecture, when higher data rates are required, a dedicated point-to-point connection between the ADT and the sensor can be preferable to optimize data exchange. Alternatively, a fiber optic connection such as FDDI can be suggested; interfaces on copper media such as Gigabit Ethernet still relies on commercial HW only, thus do not appear as a suitable choice for a airborne military application. Similar considerations can be made for GDT architecture.

Finally, to maintain compatibility to non-standard output sensors and to commonly employed data bus, it is advisable to take provision for installation of some analog/digital interfaces: for instance, ARINC 429 and MIL-STD-1553 interfaces can be introduced to allow digital connections up to 100 Kbit/s and 1 Mbit/s respectively (e.g. for Command&Control data communications between FMS and ADT or between Ground Control Station and GDT); CCIR BW 625/50, RS170 or CCIR PAL colour video interfaces can be introduced to maintain compatibility to analogue output EO and IR sensors. In this context, a possible implementation scheme is represented by a MIL-STD-1553 connection between FMS, ADT and payload control system plus a Fast Ethernet connection between ADT and a high speed sensor for data transmission. Of course, contemporary use of different interfaces requires the resulting overall data rate to remain within the channel constraints.

5.2.5.1 *SAR sensors*

For SAR sensors, some particular considerations are required. Two possible architectures can be suggested for UAV applications (see ref. [1]): SAR sensors with on-board pre-processing, (i.e. able to exploit raw data on UAV and prepare a synthetic image to be transmitted through the datalink) and SAR with ground processing . In the latter case, the raw data flow produced by a SAR has to be transmitted through the datalink channel at a typical bit rate over some hundreds of Mbit/s, therefore exceeding Fast Ethernet throughput (even for a peer-to-peer connection between sensor and ADT). Moreover, only lossless compression techniques can be employed at low data compression ratio (see Sec. 5.2.4): in fact, due to the particular structure of raw SAR data and their intrinsic uncorrelation, synthetic image reconstruction can be difficult (if not impossible) in case of information losses caused by compression or by errors at the demodulator. Therefore, for UAV applications a on-board processing SAR is highly recommended whenever SWP constraints can be overrided.

5.2.6 *DATA LINK INTEGRITY - SAFETY ISSUES*

Reaching BER levels as low as those required for safety critical flight phases can limit significantly the data link performance: application of forward error correction techniques could require complicated encoding/decoding schemes, while simpler repetition techniques can easily lead to unacceptable transmission delay. In both cases, a lot of redundancy is added to the data flow to be transmitted through the radio channel, thus reducing the net bit rate available. Moreover, latency and update rate are generally a major issue when speaking about safety critical data transmission: e.g., for the operator control to be effective during UAV takeoff and landing, update rates up to 50 Hz can be required and latency must be contained within few tenths of milliseconds. On the other hand, SWP considerations suggest a Time Division Multiplex (TDM) architecture to minimise terminal size and weight, as already described in [1]; such an architecture allows a more flexible link management too, by assigning a different number of timeslot to downlink or uplink depending on actual communication needs. Therefore, two opposite requirements come out: a TDM datalink would better perform sensor data transmission and additional functions such as relay and multi user communication (see Sec. 6.1.1 and 6.3.3) but each terminal should switch too frequently between TX and RX states to satisfy update rate needs. Alternatively, a datalink based on Frequency Diversity (FD) on uplink and downlink would minimise latency and transmission delay on both direction but would require more complicated terminals and worsen ECCM characteristics due to operational band reduction. A compromise solution is not foreseeable within this limits: a better approach consists in using a TDM Wide Band Data Link (WBDL) to transmit sensor data and UAV/payload Command&Control data (when they are not safety critical); an

additional Narrow Band Data Link (NBDL), based on FD architecture, can then be introduced to transmit all safety critical data requiring a high integrity level. The NBDL can also provide for secondary functions such as ATC voice relay (see Sec. 5.2.10) and handover management in case of multiple UAVs operations. Since data rate to support can be limited to a hundred of Kbit/s, NBDL can operate at considerably lower frequencies than WBDL, e.g. in the VHF/UHF band: this allows for much lower propagation losses and large link budget margin even for limited transmission power. Since critical flight phases such as takeoff and landing usually take place within a limited distance from the GDT (say less than 30 Km), a very low BER can be guaranteed.

5.2.7 *ECCM PROTECTION*

Military UAVs usually require a high jamming resistance capability: this feature can be achieved through Spread Spectrum ECCM techniques. A comparison between Frequency Hopping (FH) and Direct Sequence (DS) techniques is presented in [1], where advantages of FH are underlined. Generally, frequency changes ("hops") can be performed according to a pseudo-random sequence or according to a deterministic sequence: the latter technique is better identified as "Frequency Agility".

Pseudorandom Frequency Hopping ensures higher jamming resistance because the jammer, in order to achieve maximum effectiveness through narrow band emission, must reconstruct the frequency pattern; this is possible only by knowing the pseudorandom sequence generation law. On the other hand, this technique requires a quite complex handshake between terminals during link initialisation phase, thus possibly introducing synchronisation delay in case of temporary link loss. Conversely, Frequency Agility implies a slight reduction in jamming resistance (depending on the complexity of the deterministic hop sequence) but allows for a simpler synchronisation mechanism: this is a major issue when multiple terminals synchronisation is required, e.g. when the UAV is used as a relay platform (see Sec. 6.1.1) or as a communication router. (see Sec.6.3.3).

5.2.8 *DATA PROTECTION*

Data protection becomes mandatory when UAVs are used in a hostile environment and are subject to possible threats. However, some distinctions have to be made: generally, encryption of all information related to enemy field can be considered useless, if not detrimental. In fact, with this approach, every user is forced to employ a decryption unit to exploit data (see Sec. 6.1.1 and 6.3.3). On the other hand, a high security level could be required for UAV Command&Control data only (navigation parameters, flight plan, etc.) and intelligence data (e.g. when the UAV is used as a relay platform, see Sec. 6.1.1). These selected data typically require a limited transmission rate (from some tenths of Kbit/s to about 1 Mbit/s): using private key scramblers as encryption/decryption devices, no redundancy is introduced, so that protected data bit rate can still be considered a small amount of overall bit rate. To allow an easy change of scrambling keys, a Datalink architecture based on a separate encryption module (EM) is recommended and two possible connection schemes can be depicted (in the following we will refer to ADT architecture; these cosiderations can be easily extended to GDT architecture). In the first case, selection of data to be encrypted/decrypted is made inside the ADT, data are sent to the EM through a proprietary interface, processed and then sent back to the same terminal to be transmitted over the datalink (encrypted data) or to be assigned to user interfaces (decrypted data). This architecture avoids introduction of new interfaces towards FMS but implies a heavier internal ADT processing and requires more complicated control protocol (FMS must communicate to ADT which data must be protected and which not). Alternatively, data to be scrambled can be selected at the origin by FMS and, if necessary, sent to the EM; the latter is connected to the ADT through a proprietary interface; encrypted data are then managed inside the same terminal as they were coming from one of the additional interfaces described in Sec. 5.2.5. For data decryption, a similar process can be depicted. This solution presents some advantages: ADT internal processing is simplified while FMS needs only to redirect data to be protected to a different interface when encryption is required; if no data protection is needed, data can be sent to ADT via the usual Command&Control interface and the ADT to EM interface can be simply inhibited. Moreover, if the EM is equipped with a Fast Ethernet interface, as indicated in Sec. 5.2.5, it can be connected to the common bus and be addressed by the FMS as a general user: in this case no dedicated FMS to EM interface is required. This architecture is included in the general block schemes for ADT and GDT represented in Figure 7 and Figure 8.

5.2.9 *ADT ANTENNA CONFIGURATION*

At present, several UAVs use vertically polarised directive antennas mounted onto a steerable platforms. Commonly employed horn antennas feature an elevation beamwidth of some tenths of degrees in elevation plane and are steerable only in azimuth plane. However, it can be easily verified that antennas with wider elevation lobe (say 100 degrees or more) would improve system performance by allowing UAV larger attitude angles (pitch and roll) without link losses due to pointing mismatch. A simple horn with larger half-power lobe would excessively reduce the link operational range; therefore, three alternative architectures can be suggested:

- antenna unit equipped with two horn antennas instead of a single one: each horn is mounted with an opposite tilt angle with respect to UAV horizontal plane and can be selected separately accordingly to attitude angles relative to GDT antenna. The two horns are then jointly steerable in azimuth plane. Therefore, the "composite" elevation beamwidth can be widened up to 2 times that featured by a single horn, while azimuth coverage and RF gain are still guaranteed;
- antenna unit equipped with a single horn antenna mounted onto a 2-axis stabilised platform;
- antenna unit equipped with a synthetic aperture antenna (phased array) mounted on an azimuth steerable platform.

The first solution allows usage of rugged standard horns, thus limiting development costs of these parts, and permits a relatively simple antenna unit control: a discrete signal for "upside" or "downside" antenna selection is added to azimuth steering control. On the other hand, a branching waveguide section and a switching unit to be mounted onto the mobile part of the steerable platform are needed, thus increasing size and RF losses with respect to the single antenna solution. Moreover,

only elevation pointing mismatches can be recovered, but not depolarisation effects.

The second solution allows a complete recovery of every pointing and depolarisation mismatch but requires a sophisticated stabilisation and pointing system, thus increasing size and weight and complicating antenna unit control (antenna pointing and platform position must be determined in real time accordingly to mutual positions of ADT and GDT and to the UAV attitude angles).

The third solution is, potentially, the more flexible: phased arrays can be very light and offer static control of lobe direction. However, some further considerations are necessary: for instance, using three fixed arrays, a minimum 140 degrees lobe excursion in azimuth plane would be necessary to achieve RF coverage in all directions on the same plane and ensure a suitable superposition of operational angles for each antenna unit (thus avoiding spurious switching between antenna units at the separation edges). Performing such a wide lobe excursion is not a trivial task: main lobe enlargement, side lobe level increase and cross-correlation components strenghtening must be limited by carefully controlling each array element, therefore an accurate antenna unit design and simulation phase is required. A simplified approach consists in mounting each phased array on a azimuth steerable platform and electronically controlling the lobe direction only in the elevation plane, possibly at discrete steps, thus eliminating pointing mismatches due to UAV attitude angles.

In conclusion, the first solution appears as the best compromise when costs have to be reduced and limited UAV performances are required in terms of operational manoeuvres (speed, turn radii and climb/descent rates).

The second one allows the largest attitude angles, but is probably the more expensive. By the way, it can become mandatory when the link must be maintained locked while the UAV executes manoeuvres at roll/pitch angles higher than 25-30 degrees, especially at a limited distance from the GDT (i.e., few tenths of kilometres). These conditions are typically verified when a UAV travelling at medium-high speed (say, over 250 knots) performs a turn with a radius lower than 10 Km.

The third solution presents intermediate advantages, featuring good coverage performances but requiring higher development costs.

5.2.10 *INTEGRATION WITH ATC/ATM*

At present, in many countries UAV flight is limited to restricted military area only. These rigid limitations should be loosen in the next future, but, in order to operate an UAV over civil areas or, in general, outside reserved spaces, interaction with ATC is mandatory. Due to lack of specific regulations, it is logic to extend present ATC rules to UAVs; the latter can be considered equivalent to a manned aircraft whose crew is not really hosted onboard, but is located at the Ground Control Station. Since it is unforeseeable to change communication standards and equipment at the ATC side, the Data Link system must provide for all necessary functions to establish a link between the "remoted" crew and the ATC centre.

In other words, the Airborne Data Terminal (ADT) must operate as a bidirectional Relay platform for voice communications between the crew at Ground Station and the ATC operator: therefore, the ADT needs to be integrated to a suitable communication device (ATC terminal) capable to establish a connection with ATC (e.g. a VHF radio). Moreover, the ADT must be equipped with an analog-to-digital and digital-to-analog voice conversion unit to convey the ATC operator's voice onto the Data Link channel and reconvert the UAV pilot's voice into analog form before trasmission towards ATC. A similar function must be implemented at the Ground Control Station. The data rate requested can be relatively low (e.g. 2.4 Kbit/s for good quality compressed data) but must be taken in account when a Narrowband Data Link is used for the voice transmission (see Sec.5.2.6).

Integration with future ATM systems is much more complicated, due to the variety of messages that should be exchanged between UAV and ATM ground centres and the required higher integration level between the Data Link system and the whole Airborne Navigation System. A dedicated processing/interface unit must be designed to allow functional interconnection between Data Link system and one ore more ICAO standardised equipment for ATM, that is Mode-S transponder, VHF Data-Link (VDL) and Narrowband Satcom Data Link.

6. PROPOSED DATA LINK ARCHITECTURE

Accordingly to NIAG SG53 recommendations, a suitable UAV communication system capable to satisfy the above requirements can rely on a double Data Link architecture: a Wide Band Data Link (WBDL), whose primary functions are sensors data trasmission and aircraft/payload Command and Control, broadcasting and communications relay, and a Narrow Band Data Link (NBDL), whose primary function is to enhance Data Link integrity during safety critical flight phases.

To ensure maximum flexibility, a variety of interfaces towards external communications systems is also included. Sec. 6.1 presents the main WBDL features, Sec. 6.2 those of NBDL, while in Sec. 6.3 are depicted all the additional functions/characteristics that can be optionally included to satisfy all new requirements.

6.1 WBDL Main characteristics

6.1.1 *WBDL DATA LINK FUNCTIONS*

To fulfil long range (see Sec. 4.1) and communications requirements (see Sec. 4.3) the WBDL will perform three functions:

- a **point-to-point link**: it ensures connection between a main Ground Data Terminal (GDT) - equipped with a highly directive tracking antenna for long range operations and a medium gain steerable antenna for close-in operations - and the Airborne Data Terminal (ADT) - equipped with two or three selectable, medium gain steerable antennas. The point-to-point link is bi-directional and performs sensor data transmission to the GDT (downlink) and UAV/payload Command&Control during normal flight (uplink).
- a **broadcast additional link**: it ensures connection between the ADT and one or more GDT or Portable Ground Data Terminal (PGDT) (see Sec. 6.3.2). A omnidirectional antenna mounted onto the UAV can be activated and fed with the same signal sent through the point-to point data link, thus realising the sensor data dissemination function over a large territory. In this case, the broadcast link is merely unidirectional, that is no handshake is considered between ADT and GDTs/PGDTs.

- a **data relay function**: this feature can be useful to overcome line-of-sight constraints in case of OTH missions or in presence of natural obstacles along flight path: a Relay ADT (RADT) act as a signal repeater between the mission UAV and the GDT. From the communications point of view, this function can be seen as a particular case of the preceding item if we consider that the RADT acts as a router between only two users. In practice, some differences are to be considered: for instance, to maintain a suitable operational range, the RADT will use the airborne steerable antennas (and not the omnidirectional one) to establish links towards both GDT and mission UAV. Moreover, the GDT must be able to manage both RADT and mission UAV/payload Command&Control data and those data must be multiplexed and transmitted along with sensor data.

6.1.2 *WBDL OPERATIONAL FREQUENCY*

Accordingly to NATO/CEPT recommendations, the WBDL should operate in J band (14.62 - 15.23 GHz): in fact this band is defined as following:

- NATO Harmonised Band type 1 (i.e band in general military use in NATO)
- "essential military required for fixed/mobile military systems" (i.e. its unavailability would have effects on operativity of NATO forces)
- recommended for UAV Command&Control and real-time trasmission of images.

6.1.3 *WBDL DATA LINK MANAGEMENT*

As indicated in [1], the WBDL better performs its functions operating on a Time Division Multiplex basis to accomplish SWP constraints. This architecure also allows a SW dynamic allocation of timeslots on downlink and uplink, thus sharing the overall bit rate on the two directions in order to accomplish different functions as data relay (see Sec. 6.1.1) and communications within a tactical network (see Sec. 6.3.3)

6.1.4 *WBDL OPERATIONAL RANGE AND DATA RATE*

As described in Sec. 5.2.1, operational range is a function of a variety of parameters including GDT and ADT antenna gain, EIRP and bit Rate. A suitable configuration features a high gain GDT antenna (a medium-high gain PGDT antenna) and up to three elevation fixed, azimuth steerable ADT antennas. Moreover, accordingly to considerations depicted in Sec 5.2.3, a data rate selection capability can be useful to optimize perfomances depending on actual needs. For example, two possible data rates can be proposed: a speed of about 2.5 Mbit/s can be used when medium data rate sensors are employed, thus extending ranges up to 200 Km with solid state RF amplifier or up to 250 Km with small vacuum tube RF amplifier. The transmission speed can then be switched up to 12 Mbit/s when high data rate sensors are used: in this case the operational range must be reduced at about 125Km and 150 Km respectively.

6.1.5 *WBDL BIT ERROR RATE*

The link budget should be designed to guarantee a Bit Error Rate (BER) of about 10^{-3} - 10^{-4} for raw data; such a figure can be considered good for data produced by typical imaging sensors. A lower BER value (such as 10^{-7}) will be obtained on selected data (typically Command&Control data and intelligence data) through forward error correction techniques: cyclic codes such as Golay and BCH classes, associated to interlaeaving/deinterleaving modules appears as a good compromise among coding efficiency, error bursts recovery, bit rate increase and implementation complexity.

6.1.6 *ECCM PROTECTION*

Accordingly to considerations indicated in Sec. 5.2.7, Frequency Agility techniques ensure a suitable jamming robustness associated to a multi-user synchronisation capability for relay and communications purposes.

6.1.7 *MULTI-SENSOR CAPABILITY AND EXTERNAL INTERFACES*

Both ADT and GDT can be equipped with a standard Fast Ethernet interface and use TCP/IP as network protocol: this enhance interoperability and allows multi-sensors operations by permitting sensors connection to a common bus. To extend interoperability to present sensors equipped with analogue interfaces and to widely used data bus, ARINC429, MIL-STD1553 digital interfaces and CCIR 625/50, RS170 and CCIR PAL analogue video interfaces can be optionally included.

6.1.8 *DATA COMPRESSION*

JPEG data compression with compression ratio up to 15:1÷20:1, selectable by user at discrete steps depending on image resolution/quality desired, appears as the best choice

6.1.9 *DATA MULTIPLEXING-DEMULTIPLEXING*

In order to perform all their functions, ADT and GDT must have respectively data multiplexing and demultiplexing capability. Data multiplexing is performed at ADT by Fast Ethernet bus (see Sec. 6.1.7), that allows multiple users connection with different TCP/IP addresses. A further, internal data multiplexing level is introduced to allow transmission of data from supplemental interfaces (video, MIL-STD1553, etc.) and from encryption module (see Sec. 6.1.10). Similarly, at GDT, data coming from datalink are internally demultiplexed and sent to Fast Ethernet interface, supplemental interfaces (if present) and encryption module. A further data demultiplexing is performed on Fast Ethernet bus via different TCP/IP user addresses.

6.1.10 *DATA ENCRYPTION*

To ensure data security, both ADT and GDT can be equipped with an external encryption/decryption module to be connected as in Figure 7 and Figure 8.

6.1.11 *WBDL ANTENNAS*

The proposed architecture uses a highly directive, reflector type steerable antenna with precision autotracking capability (based on monopulse technique for azimuth tracking and power derivative technique for elevation tracking). For close-in operations, a secondary horn antenna is mounted over the main one and performs its functions in parallel. Both antennas operates in vertical polarisation. The GDT Antenna mount hosts the Radio Frequency Unit and the RF power amplifier (see Sec. 6.1.4). Moreover, a tilt sensing unit is incorporated for mount attitude angles compensation.

The ADT Antenna units must be chosen accordingly to specific UAV requirements, as indicated in Sec. 5.2.9. By the way, usage

of a double horn antenna unit appears more probable, even if a feasibility study for a patch array antenna unit is in progress.

6.2 NBDL main characteristics

6.2.1 *NBDL FUNCTIONS*

As introduced in Sec.5.2.6 and Sec.6, NBDL main function is the redundant transmission of UAV Command&Control Data in order to achieve high integrity for safety critical flight phases; moreover, NBDL can act as an emergency link in case of failure of the WBDL, thus allowing UAV control until the end of the mission. The NBDL also support the ATC relay function and can be optionally used to manage handover when a UAV has to be controlled by two GDTs or to ensure connection to multiple UAVs.

6.2.2 *NBDL OPERATIONAL FREQUENCY*

Accordingly to NATO ARFA recommendations and considerations depicted in Sec. 5.2.6, NBDL could operate in the VHF/UHF band from 230 to 400 MHz. Use of higher frequencies can be considered accordingly to data rate requirements (see Sec. 6.2.4).

6.2.3 *NBDL DATA LINK MANAGEMENT*

In order to guarantee high update rate and low latency, the NBDL uses a Frequency Diversity technique to transmit over downlink and uplink (see Sec. 5.2.6)

6.2.4 *NBDL OPERATIONAL RANGE AND DATA RATE*

The NBDL can operate at distances up to 150 Km at data rates between 25 and 500 Kbit/s by using ground and airborne omnidirectional antennas. The definite data rate value must be chosen accordingly to actual needs: both UAV Command&Control function and additional functions such as ATC voice relay, when required, must be. If the range has to be increased, usage of a GDT directional antenna must be considered.

6.2.5 *NBDL BIT ERROR RATE*

The link budget is dimensioned to achieve a BER level of about 10^{-4} for raw data. Through Forward Error Correction Techniques, the actual data rate is cut down to 10^{-8}-10^{-9}, thus a good value to ensure suitable UAV control even during critical flight phases.

6.2.6 *ECCM PROTECTION*

For NBDL a dedicated Frequency Hopping technique is advisable to enhance its ECCM protection level. Standard hopping protocols, such as HAVEQUICK or SATURN can be considered to increase interoperability.

6.2.7 *NBDL INTERFACES*

The NBDL features a dedicated interface to the corresponding WBDL terminal that support both NBDL Command&Control data and transmission data.

6.3 Data Link system extensions

6.3.1 *INTERFACES TO EXTERNAL COMMUNICATIONS EQUIPMENT*

In order to fulfil all requirements indicated in Sec. 5.2.10 and allow the integration with Command&Control standardised Data Links (e.g. LINK16) and SATCOM devices, an additional module called Data Link Interface Processor (DLIP) can be introduced, as indicated in Figure 7 and Figure 8. This module is connected to the WBDL through an additional interface and performs all data processing functions necessary to convey information from the auxiliary communication systems to the WBDL and viceversa. For instance, it can encompass an autonomous CPU plus a vocoder for ATC relay function, a serial interface to communicate with the SATCOM terminal and so on.

6.3.2 *PORTABLE GDT (PGDT)*

To exploit all Data Link functions, including broadcasting and relay (see Sec. 6.1.1) and communication routing (see Sec 6.3.3), a portable GDT (PGDT) can be added to standard Data Link configuration. The PGDT has nearly the same function of GDT, even with reduced performances. It is based on three functional units: a RF/processing unit (RFPU, with size and weight similar to ADT), an Antenna Unit (AU) and a Data Exploitation Unit (DEU). A block scheme is depicted in Figure 9.

The RFPU unit provides for the following functions: RX/TX, modem, data multiplexing/demultiplexing. It is equipped with the same interfaces of GDT: in particular, a Fast Ethernet interface is used for connection to the DEU. If necessary, both DEU and RFPU can be connected onto a common bus.

The AU is based on a medium gain reflector antenna with steering capability in azimuth and elevation planes and is mounted on a ruggedized mast. It is equipped with tilt sensors to compensate for mount attitude angles and with a GPS plus a magnetometer device for geodetic position self-determination. The AU can be pointed accordingly to data provided through the DEU or via external interface. Once the link is locked, UAV tracking is ensured thanks to a power derivative algorithm in both azimuth and elevation planes; if required, tracking can be based upon telemetry data sent by the ADT.

The DEU is a small portable unit to be connected to the RFPU via a Fast Ethernet interface: it is equipped with a monitor for sensor data visualisation and AU/ RFPU control. The DEU also allows to reconfigure the PGDT to be used in the Tactical Network mode (see Sec. 6.3.3).

Finally, the DEU can be omitted and the RFPU can be connected directly to a Ground Station similar to that used for the GDT.

6.3.3 *WBDL COMMUNICATION FUNCTION - TACTICAL NETWORK*

If required, both ADT, GDT and PGDT (see Sec. 6.3.2) can be SW reconfigured to define a local tactical communication network: in this context, the ADT act as a communication router between up to 8 ground users (i.e. the GDT and up to 7 PGDT) on a Time Division Multiplex basis; each user can be assigned a variable number of timeslots, depending on its transmission and reception bit rate needs, provided that the overall bit rate available is not exceeded. In this case each connection is bi-directional and point-to-multipoint or multipoint-to-point communications are possible. PGDTs are connected to the ADT via the airborne omnidirectional antenna, while the airborne steerable antennas are used to ensure the link to GDT;

UAV/payload Command&Control functions still rely on ADT-GDT link.

7. ACKNOWLEGMENTS

The authors wishes to acknowledge the Italian Ministry of Defence for their interest and Mr. Ugo Squillari and Mr. Lorenzo Carbonini of Marconi Communications - Genoa - Italy for their precious contribution.

8. REFERENCES

[1] L.Bianchi, G. Battaini, G.L.Scazzola, E.Crovari - "Integrated Data Link for UTA Applications: Design Consideration and Development Results" - AGARD-CP-594 pages 21-1..21-15 - Oct. 1997

[2] U.S. Defense Airborne Reconnaissance Office (DARO) - "UAV Annual Report - FY 1997"

[3] John G. Proakis - "Digital Communications" -2nd edition - Mc Graw Hill - Singapore, 1989

IR IMAGE

SAR IMAGE

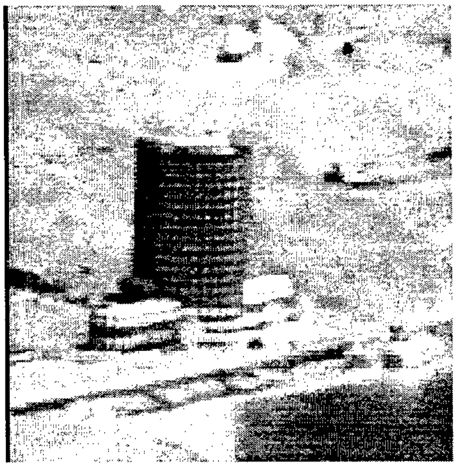

Figure 1 (original)

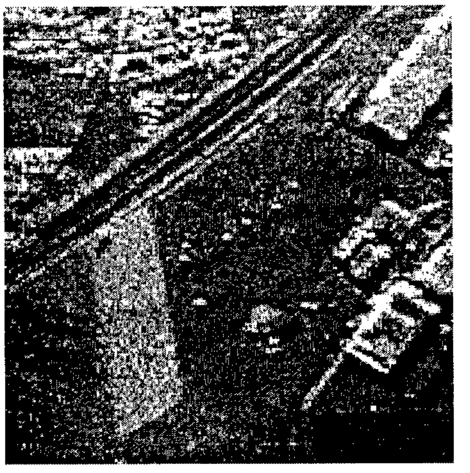

Figure 4 (original)

Figure 2 (JPEG compression 25:1)

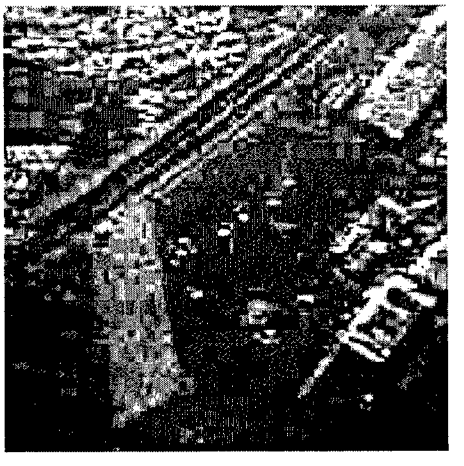

Figure 5 (JPEG compression 30:1)

Figure3 (Wavelet compression 25:1)

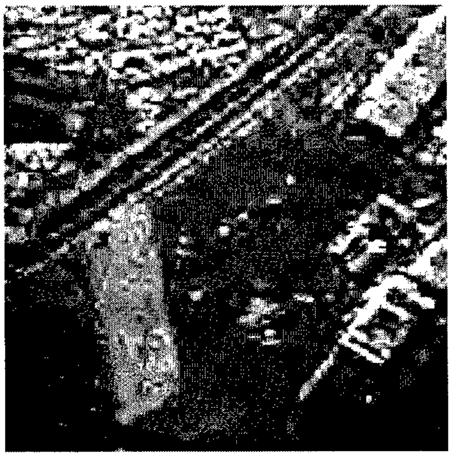

Figure 6 (Wavelet compression 30:1)

Image	Compression type/ratio	Coding time (sec)	Decoding time (sec)	MSE	PSNR (dB)
Figure 2	JPEG 25:1	0.6	0.3	79	29.15
Figure 3	Wavelet 25:1	32.8	8	95.3	28.33
Figure 5	JPEG 30:1	0.4	0.2	44.3	31.6
Figure 6	Wavelet 30:1	32.1	8	50.3	31.1

Table 1

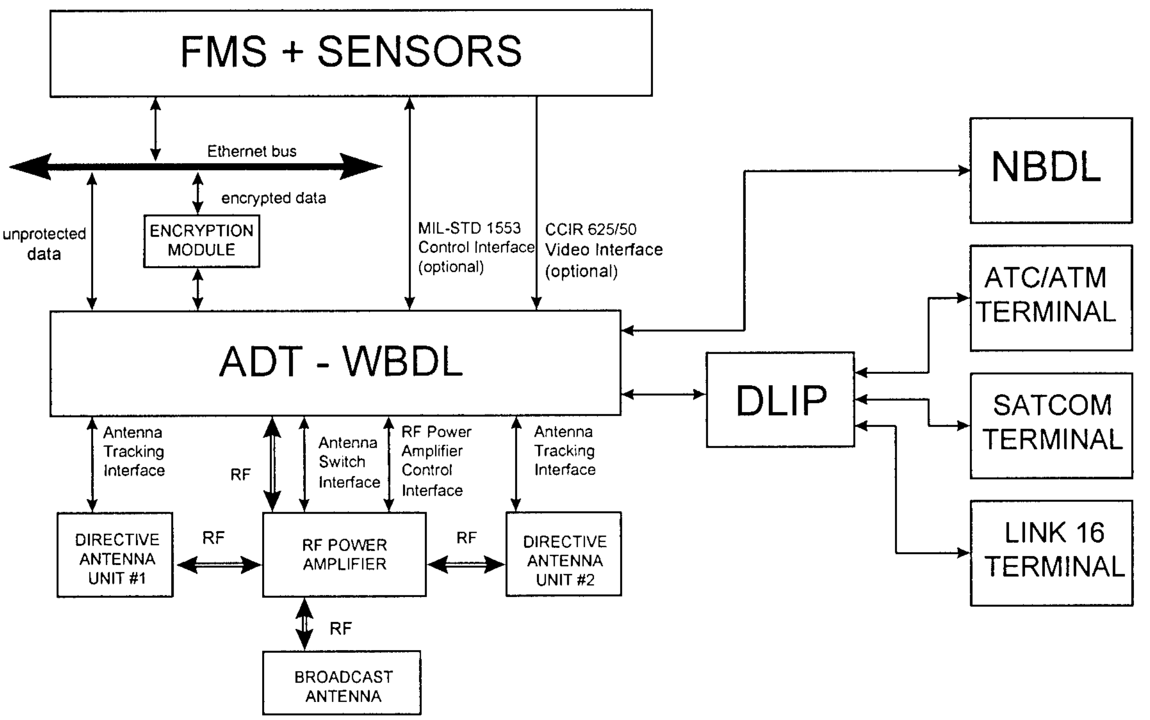

Figure 7

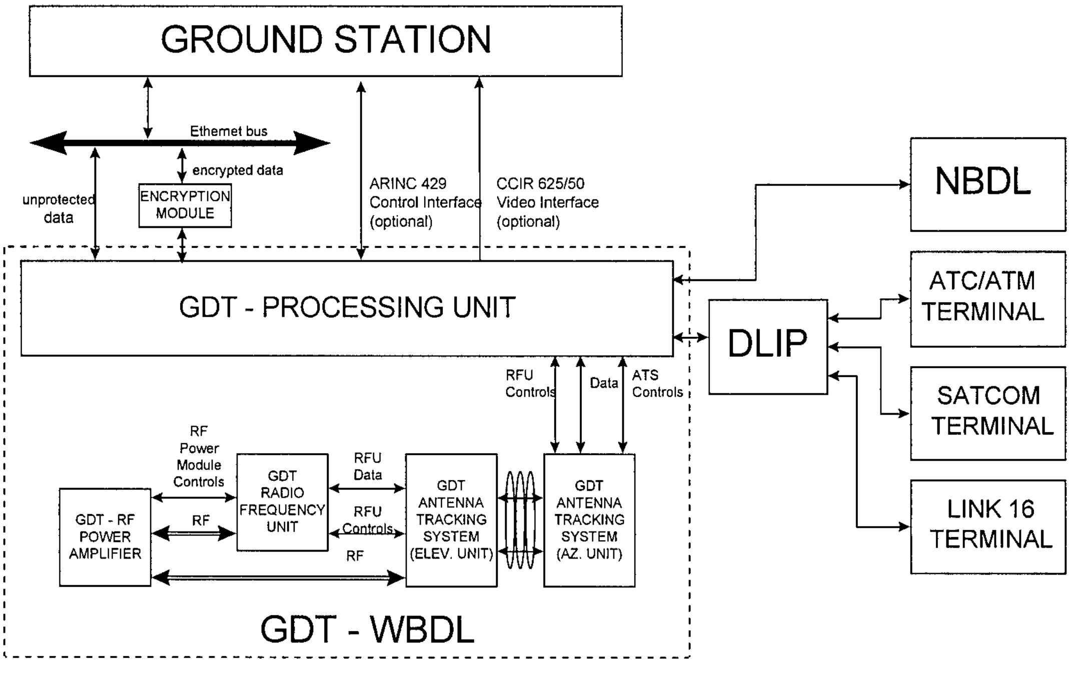

Figure 8

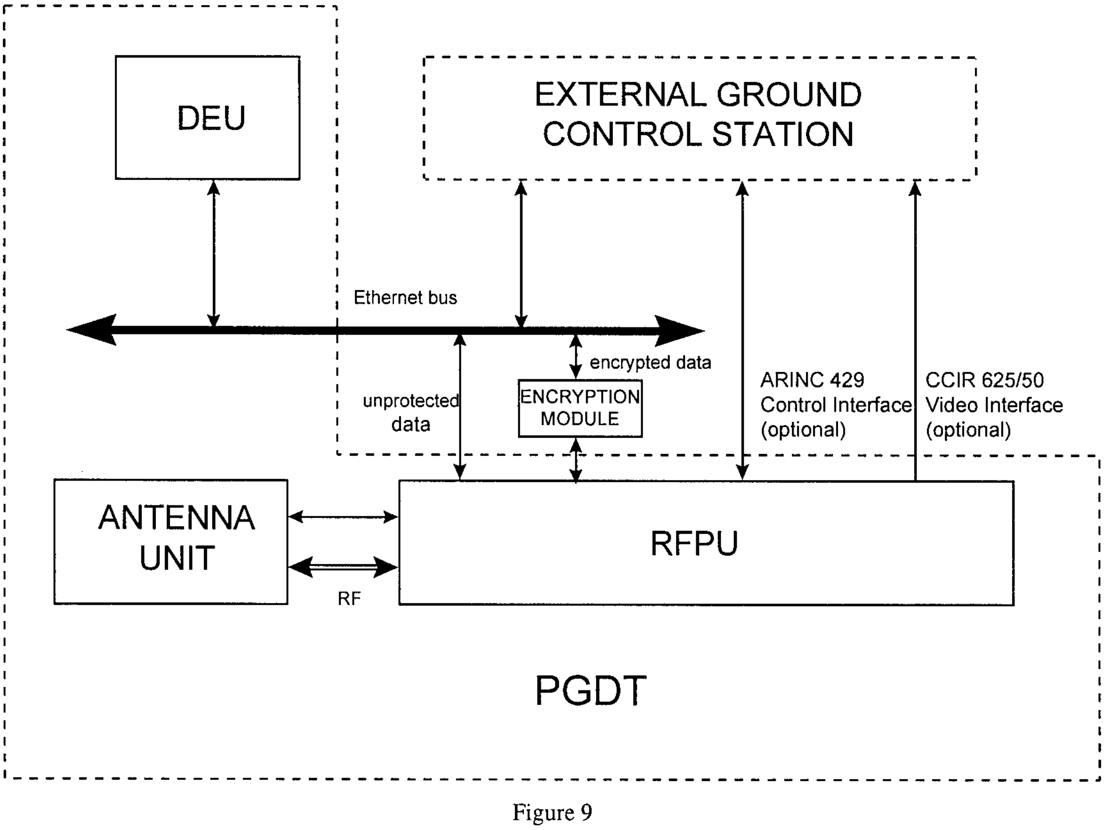

Figure 9